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Review

Pretreatment and feeding of biomass for pressurized entrained flow gasification

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ABSTRACT

In our contribution we have compared advantages and disadvantages of four different methods for biomass (wood) thermal pretreatment and grinding for feeding of the biomass-fuel to pressurized entrained flow gasifier. The four methods of pretreatment and feeding involve drying, torrefaction, flash pyrolysis and dissolution of wood in organic solvents.

The resulting fuels after pretreatment are compared in terms of heating value, grinding energy needed, overall efficiency of conversion (from raw biomass to fuel), auxiliary energy needed, fluidization properties, pneumatic feeding properties, pumping, viscosity and possible changes of properties of liquids/slurry, storage, microbial attack, emissions from thermal pretreatment and overall integration with pressurized entrained flow gasification.

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1. Introduction

Biomass should replace in future, at least partly, fossil fuels. Biomass can be converted either directly to heat and electricity or transformed to gaseous and liquid fuels with possibility to utilize more sophisticated technologies for production of electricity (for example in fuel cells, gas turbines etc.) [1–5]. Conversion of woody biomass to gaseous and liquid fuels is often done by thermal processes — gasification and pyrolysis. High requirements on produced syngas purity call for either adoption of gas cleaning methods [6] or for choosing a gasification method producing relatively clean syngas, particularly low content of tar. Pressurized entrained flow (EF) gasification of coal by oxygen is relatively developed and applied method [7]. Such method of gasification for woody biomass is still under development [8,9]. Beside problems with slagging behavior of ash in high temperature gasification of biomass [9] there are high requirements and problems in feeding of biomass (wood) to entrained flow pressurized gasifiers [8,10,11]. Characteristic temperatures (softening, melting) for willow ash and straw ash [12,13] are summarized in Table 1. Soft biomass (straw, grass) is preferable for slagging regime because of the lower melting point of ash.

Main problems in feeding of wood to EF pressurized gasification are caused by high requirements on disintegration of wood (biomass) and separation of pressurized conditions in the gasifier from atmospheric conditions in the feeding line. In principle three basic forms of wood and thermally treated wood are suitable for feeding:

a) powder wood [11,14] or torrefied powder wood [15–17]
b) slurry of either bio-oil with char [8,18,19] or char/wood dispersed/partly dissolved in glycerol, ethylene glycol, phenolic-oil, or a bio-liquid [20–22]

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Table 1
Measured ash characteristic temperatures for willow, spruce, wheat straw and grass ashes [12,13].

Character. temperature (°C)	Willow ash	Spruce ash	Wheat ash	Grass ash
Sintering temperature	~1380	1250–1390	800–860	890–980
Softening temperature	~1540	1410–1640	860–900	960–1020
Hemispher. temperature	~1550	1500–1700	1040–1130	1040–1150
Melting temperature	~1560	1550–1750	1080–1180	1140–1200

c) wood practically totally dissolved in a liquid solvent (e.g. ethylene carbonate) [23,24].

Feeding (pumping) of liquids and slurries to the EF gasifier under pressurized conditions has advantage in relative simplicity and in principle in no need of auxiliary gas (N_2, CO_2 etc.) for the feeding. On the other hand feeding of wood or thermally treated (torrefied) wood needs for a smooth feeding to the EF pressurized gasifier special measures (e.g. lock hoppers, pressurized pneumatic transport) or for lower operating pressures mechanically sealed piston feeding for separation of spaces with different pressures. To suppress fluctuations in feeding special measures must be often taken (e.g. vibrators, feeding from non-bubbling fluidized bed etc.).

This study is targeted to comparison of those above mentioned feeding methods of biomass for entrained flow pressurized gasification by oxygen from the point of view of energy consumption, reliability, operating problems, biomass storing problems, necessity of utilization of auxiliary gases etc.

2. Feeding of biomass into EF pressurized gasifier

For EF gasification with relatively short residence time of fuel particles in the reactor the biomass particles must be sufficiently small, relatively dry and they should be transported from atmospheric conditions to pressurized conditions in the EF reactor.

Size reduction of biomass (grinding, milling, pulverization) requires milling/grinding equipment. Power consumption in disintegration of biomass depends on biomass character (soft and hard wood, herbaceous biomass) content of moisture, extend of size reduction and way of disintegration.

Effect of wood moisture content (MC) and thermal treatment (torrefaction) of willow wood on consumption of electric energy of cutting mill used for size reduction to given particle size is shown [25] in Fig. 1. For pulverization of particles to average size below 0.2 mm vibration mill is recommended [14]. Consumptions of electric energy for cutter mill and vibration mill in a broader range of particle average size are compared in Table 2. At present new methods for wood chips disintegration are being developed, like freezing pulverization or explosion disintegration. Their power consumption is however probably relatively high.

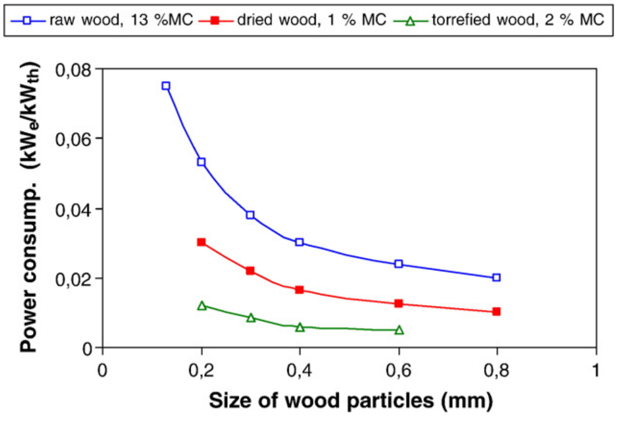


Fig. 1. Comparison of power consumptions for milling of raw, dried and torrefied willow wood to final average sizes between 0.2 and 0.8 mm. Electric power consumption (in kW_e) is related to thermal energy of the mass flow of wood based material (in $kJ/s = kW_{th}$).

Al the stated relative power consumptions consider consumption of electric power or energy related to thermal power or energy (heating value) of the wood. It means, that if we consider 33% efficiency of power generation from biomass the relative consumption of energy related to heat energy of wood should be tripled (10–18% of fuel heat content).

Power consumption for milling of some evaluated species of wood from trees with leaves (beech, larch, willow) has indicated the order in energy needs:

willow > beech > larch

Bark has approximately 1/3 energy needed for milling in comparison with corresponding wood [26]. The electric energy consumption needed for disintegration of lignocellulosic materials (in kWh_e/t) is several times higher than for coals [26].

Pulverized fuel feeding system for coal feeding to pressurized EF gasifiers (reactors) can be applied to biomass (wood) under assumption that the properties of biomass particles are similar. Generally a dense phase pneumatic transport, fluidized bed and lock hoppers with an inert gas could be considered. Pneumatic transport systems are not suitable for fibrous and needle-like biomass materials. Fluidization of pulverized wood (d_p<0.2 mm) is also difficult [13,27], because of high cohesion forces among the particles and chanelling. In pneumatic feeding and lock hoppers only non-condensing inert gases and vapours can be considered (nitrogen, CO_2 and superheated steam) [28]. Screw feeding of wood powder suffers from fluctuations of flow rates [11] and some corrections (e.g. vibration slabs) should be connected to them to smooth the feeding. Due to problems with high energy consumption and feeding of small wood particles conceptions of feeding bigger wood particles (about 1 mm) have been suggested [13].

Pressurizing of biomass fuels to high pressures (over approx. 2 MPa) is mediated by lock hoppers, pressurized usually by an inert gas (N_2 or CO_2). The electricity consumption for compression of the inert gas [13] is estimated for lock hoppers system to be about 0.025 kW_e/kW_{th} (wood). Another possibility for pressurizing to relatively lower pressures (less than approx. 1.8 MPa) is piston feeding. The gas leakage through the piston feeder is estimated to be about 0.1 m^3/ton. Total consumption of electric power for this pressurizing method and for compressed gas is estimated to be 0.01 kW_e/kW_{th} (wood) [13].

3. Production and feeding of torrefied biomass into EF pressurized gasifiers

Biomass (wood, straw, grass) torrefaction is a mild pyrolysis process that improves the fuel properties. The main changes in biomass due to torrefaction involve decomposition of hemicellulose, partial depolymerization of lignin and cellulose (shortening of cellulose macrofibrils). Torrefied wood has a hydrophobic nature — it means better storage properties than dried wood. The torrefied wood is more brittle with much better milling properties. The specific calorific value of

Table 2
Comparison of power consumption in cutter and vibration milling of wood.

	Final average size (mm)	Estimated power consumption (kW_e/kW_{th})
Vibration mill	0.035	0.06
Vibration mill	0.2	0.03
Cutter mill	0.2	0.055
Cutter mill	1	0.014

Table 3
Composition (mass %) of dry willow wood and torrefied willow wood [30] from laboratory experiments.

	Wood	Torrefied wood (250 °C, 30 min)	Torrefied wood (300 °C, 10 min)
Carbon	47.2%	51.3%	55.8%
Hydrogen	6.1%	5.9%	5.6%
Oxygen	45.1%	40.9%	36.2%
Nitrogen	0.3%	0.4%	0.5%
Ash	1.3%	1.5%	1.9%
LHV (MJ/kg)	17.6	19.4	21.0

torrefied wood is higher than that of the original wood. In principle there are two ways of torrefaction: wet process [29] and dry process, resembling on more intensive drying at higher temperatures [30]. Disadvantage of the wet process [29] is necessity to remove excessive water from the torrefied biomass and liquid effluents with relatively high content of organics and mineral salts.

Typical conditions for dry torrefaction are: temperature range 230–300 °C, near atmospheric pressure, absence of oxygen and relatively low particle heating rate (less than 50 °C/min) during the process. The biomass is partly decomposed and the product has higher content of carbon, lower mass and higher LHV/kg than the input biomass. The yield of mass and energy from the original biomass to torrefied biomass is strongly dependent on torrefaction temperature, reaction time and biomass type. Composition of dry willow wood is compared with torrefied wood for two different torrefaction conditions in Table 3.

The mass yield and energy yield at different temperatures of torrefaction process applied to grass, straw and willow wood are compared in Table 4.

$$\text{Mass yield}(Y_{\text{mass}})\text{ in mass }\% = \left(m_{\text{product}}/m_{\text{feed}}\right)_{\text{daf}} {*}100 \tag{1}$$

$$\text{Energy yield }\left(Y_{\text{energy}}\right)\text{in }\% = Y_{\text{mass}} {*} \left(\text{HHV}_{\text{product}}/\text{HHV}_{\text{feed}}\right)_{\text{daf}} \tag{2}$$

Mass and energy yields are lower in torrefaction of grass and straw in comparison with woods. For torrefaction of wood at temperatures between 250 and 300 °C the typical mass yield values are 70–90% and energy yields are approx. between 76 and 93%. The gas and volatiles from torrefaction generally contains carbon monoxide, carbon dioxide, water vapour, hydrogen and organic volatiles (VOC). The higher the temperature of torrefaction is, the higher combustion heat has the waste gas with volatiles from torrefaction. The combustion heat of volatiles can be exploited for autothermal operation of the torrefaction process. Torrefaction is slightly endothermic process [31] requiring approx. 0.6–1 MJ/kg (based on energetic balance of the overall process and products in HHV terms).

Table 4
Comparison of mass yield and energy yield of torrefied reed canary grass, wheat straw and willow wood [16] at three different temperatures (time of torrefaction = 30 min).

Biomass	Temperature (°C)	Mass yield (mass %)	Energy yield (% of feed energy)
Reed canary grass	250	84.0	86.6
Reed canary grass	270	72.0	77.1
Reed canary grass	290	61.5	69.0
Wheat straw	250	82.6	86.2
Wheat straw	270	71.5	78.2
Wheat straw	290	55.1	65.8
Willow wood	250	89.6	92.7
Willow wood	270	79.8	85.8
Willow wood	290	72.0	79.2

Reactor technology for torrefaction has to combine heating the biomass to the desired temperature and holding it at this temperature for a specific time [31] (usually 20–40 min). The reactor for torrefaction can be rotary kiln or multiple hearth reactor (for bigger inlet wood particle-pieces) or fluidized bed for smaller particles (dimensions in mm). Similarly as for drying of biomass [32] either indirectly heated process or directly heated process can be considered for torrefaction. The gases suitable for torrefaction (coming into direct contact with biomass) could be flue gas with very low oxygen concentration, CO_2, nitrogen, superheated steam and gases (volatiles) from torrefaction. An example of concept with directly heated torrefaction with product gas recycling is illustrated in Fig. 2.

Main differences between original wood and torrefied wood are:

- Slightly higher heating value: LVH (torrefied wood) = 21–22 MJ/kg
- Hydrophobic nature of torrefied wood — better storing properties
- Brittle character of torrefied wood with consequences in lower energy needed for milling (grinding) — see Fig. 1.

The energy consumption for milling of torrefied wood from cm pieces to size fraction below 0.4 mm is approx. 3 to 7 times lower (depending on temperature and time of torrefaction) than for untreated, partly dried wood with moisture content 12–16 mass %. Suitable temperature for torrefaction (from the point of view of possible autothermal torrefaction process and low energy consumption in subsequent milling) is between 270–280 °C, sufficient holding (residence) time about 0.5 h. The main energy penalty paid for the process of wood torrefaction with milling is on the side of the thermal process. Approximately 10–20% of the energy content of original dry wood is lost in production of torrefied wood. For straw and grass the energy loss is moderately higher (Table 4).

Fluidization and pneumatic transport properties of small, torrefied wood particles ($d_p < 150$ μm) are much better than corresponding small wood particles and their behavior resembles to dry coal particle fluidization behavior [33].

4. Production and feeding of bio-oil/char slurry into EF pressurized gasifiers

Fast pyrolysis of biomass, with optimized yield of bio-oil offers another possibility of thermal pre-treatment of biomass — transformation into liquid or slurry (together with char). This transformation enables pumping. Fast (flash) pyrolysis is a thermal process in which the biomass feedstock (wood, straw etc.) is rapidly heated (residence time typically 0.5–3 s) in the absence of air and the products are relatively quickly cooled and condensed to a brown liquid with heating

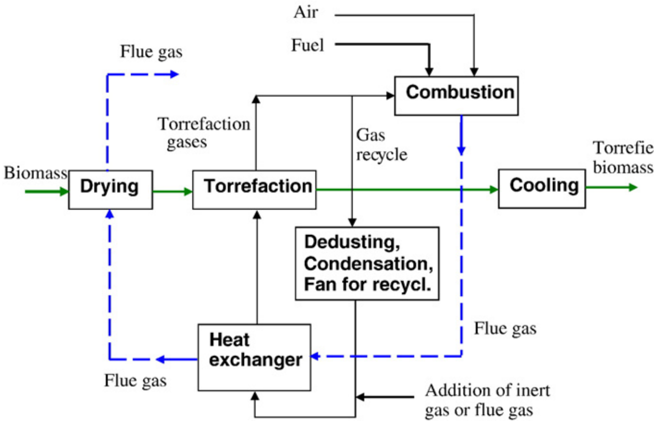


Fig. 2. Basic principle concept for directly heated, two stage torrefaction with gas recycling.

Table 5
Principles and capacities of biomass pyrolysis units [8,37].

Reactor design	Capacity (dry biomass feed)	Organization or company	Products
Fluidized bed (bubbling, stationary)	400 kg/h	DynaMotive, Canada	Fuel
	250 kg/h	Wellman, UK	Fuel
	20 kg/h	RTI, Canada	Research/ fuel
Circulating fluidized bed (CFB)	1500 kg/h	Red Arrow, Ensyn design, USA	Chemicals
	1700 kg/h	Red arrow, Ensyn design, USA	Chemicals
Rotating cone	200 kg/h	BTG, The Netherlands	Research/ fuel
Vacuum	3500 kg/h	Pyrovac, Canada	Pilot scale demonstr.
Twin screw reactor	1000 kg/h	FZK, Future energy, Germany	Fuel, slurry
Ablative		NREL, USA	Research/ fuel

value between 15 and 19 MJ/kg. Essential features of a fast pyrolysis process are [34,35]:

- Very high heating and heat transfer rates requiring feeding of relatively small biomass particles.
- Carefully controlled temperature, usually between 450 and 550 °C.
- Rapid cooling of the produced gases and vapours to give the bio-oil.

The main, desirable product, bio-oil, is produced in yields typically between 60 and 80 mass % (related to dry biomass feed). The by-products are char (12–20 mass %) and gas (10–20%) [36]. The energy yield in bio-oil and char (heating value 24–32 MJ/kg) together is about 90% [34,36].

During the period of approx. 20–30 last years a number of different reactor designs have been explored [34,37] that meet the above mentioned requirements. The reactor designs with typical capacities are given in Table 5. A principal scheme of modern facility for fast pyrolysis in circulating fluidized bed (CFB) is shown in Fig. 3.

The shift in chemical composition of bio-oil compared with wood is obvious [37] from comparison of chemical formula for composition of dry, ash free wood ($CH_{1.4}O_{0.6}$) and bio-oil ($CH_{1.9}O_{0.7}$). The main categories of compounds in bio-oils are: water, carboxylic acids, hydroxyl-aldehydes, hydroxyketones, sugars, phenolics. The bio-oil has a multiphase structure [19] and is practically immiscible with mineral oil based fuels. Very good miscibility is, however, with alcohols. Addition of an alcohol (e.g. methanol, ethanol) significantly reduces viscosity of bio-oils and retards changes during storing. Typical composition and properties of bio-oil are collected in Table 6.

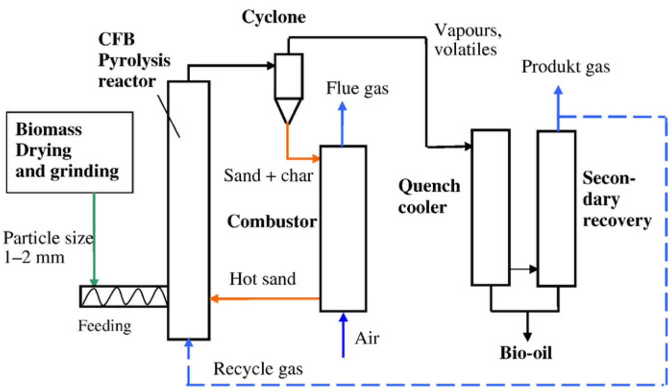


Fig. 3. Simplified scheme of CFB biomass pyrolysis unit design (a part of flue gas from combustion of char can be used in CFB reactor to elevate gas velocity).

Table 6
Properties and composition of bio-oils from various feedstocks [37].

Property	Birch	Pine	Poplar	Various woods
Content of solids (mass %)	0.06	0.03	0.045	Range: 0.01–1
pH	2.5	2.4	2.8	Range: 2.0–3.5
Water content (mass %)	18.9	17.0	16.8	Range: 15–30
Density (kg/m^3)	1.25	1.24	1.20	Range: 1.2–1.3
Kinematic viscosity at 50 °C (mm^2/s)	28	28	14	Range: 13–80
LHV (MJ/kg)	16.5	17.2	17.3	Range: 13–18
Ash (mass %)	0.004	0.03	0.007	Range: 0.004–0.3
C (mass %)	44	45.7	48.1	Range: 32–49
H (mass %)	6.9	7.0	6.3	Range: 6.8–8.5
O (mass %)	49	47.0	46.1	Range: 44–60
N (mass %)	<0.1	<0.1	0.14	Range: 0.0–0.2
S (mass %)	0.01	0.02	0.04	Range: 0.0–0.05
Na + K (ppm)	29	22	2	Range: 5–500
Ca + Mg (ppm)	62	28	2	Range: 4–600
Flash point (°C)	62	95	64	Range: 50 to 100
Pour point (°C)	−24	−19		Range: −10 to −36

Very important feature of pyrolytic bio-oil is instability and chemical/physical changes during storing. Production of bio-oils by fast pyrolysis is thermodynamically strongly non-equilibrium process. Presence of many unstable and polymerizing compounds together with low pH (presence of organic acids) and very small char particles causes commonly instability and significant changes of properties during storing (e.g. higher viscosity).

Char from fast pyrolysis of biomass can be used either for heating the process of pyrolysis (as shown in Fig. 3) or can be grinded and mixed with bio-oil [8]. As it was proved experimentally [8] properly grinded char particles (d_p<0.05 mm) in a form of slurry with bio-oil (mass ratio char/bio-oil between 0.1 and 0.25) are pumpable and relatively stable. Viscosity of char/bio-oil slurry is several times to 1 order higher than viscosity of the pure bio-oil (depending on char content) and the slurry exerts thixotropic behavior. For better pumping and spraying of the slurry in the entrained flow reactor higher temperatures should be applied (50–80 °C).

Due to content of carbonaceous char in the slurry, the average content of oxygen in such a fuel is lower than in original bio-oil, content of carbon and oxygen demand in EF gasification are higher. The lower heating value of such char/bio-oil slurry is typically 20–22 MJ/kg and the LHV resembles on heating value of properly torrefied wood.

5. Possibilities of production and feeding of other slurries into EF pressurized gasifiers

In principle grinded (pulverized) wood, torrefied wood or bio-char could be mixed with other bio-liquids, particularly waste liquids to prepare pumpable slurries. Raw glycerol (Table 7) from production of bio-diesel [38–40], waste alcohols (ethanol, propanol etc.) or phenolic

Table 7
Properties of raw glycerol from production of bio-diesel from rape seed vegetable oil [40].

Content of glycerol	77–91 mass %	Sulphates	0.01–1.04 mass %
Content of ash	3.5–7 mass %	Phosphates	0.02–1.45 mass %
Content of water	0.1–13 mass %	Acetates	0.01–6 mass %
pH	4.5–7.4	Na	0.04–2 mass %
LHV	15–17.5 MJ/kg	K	0.003–4 mass %
Kinematic viscosity	120 mm^2/s	Ca	0.1–65 mg/kg
Methanol	0.01–3 mass %	Mg	0.02–55 mg/kg
3-monopropylendiol	0.2–13.5 g/kg	Fe	0.1–30 mg/kg

compounds [41] from biorefineries are examples of such waste bio-liquids.

Glycerol has LHV similar to bio-oil (16 MJ/kg) and relatively high boiling point (290 °C). Its relatively high viscosity at lower temperature can be reduced by heating to higher temperatures or by addition of alcohols. At higher temperatures (over 100 °C) glycerin partly dissolves wood, particularly under hydrolytic and catalytic effects of acids [42] or hydroxides and alkali carbonates [43,44]. Comparison of temperature dependencies of liquefaction yields of various biomass types in pure glycerin and in glycerin with KOH is given in Fig. 4. Hazelnut shell has in comparison with beech wood much higher content of lignin and much lower content of cellulose. As can be seen from the figure, addition of KOH has dramatic effect on liquefaction of biomass in glycerin.

Research work on EF gasification of ethylene glycol and ethylene glycol/charcoal slurry confirmed better, more efficient gasification with the slurry than with pure ethylene glycol only [45] at the same stoichiometric operating conditions.

6. Possibilities of total biomass liquefaction and feeding as a liquid to EF pressurized gasifiers

It seems that ethylene glycol [46], glycerol [42–44] and particularly ethylene carbonate [23,24] are perspective solvents for ligno-cellulosic materials (wood, nut shells, straw etc.). Optimized solvolysis of wood in acidified ethylene glycol (EG) and in glycerol (temperature, time, concentration of suitable acid) can lead to more than 95% dissolution (liquefaction) of wood in EG [46] or glycerol [44].

Ethylene glycol and ethylene carbonate (EC) are not bio-liquids, but they are produced from ethylene oxide by reaction with water and CO_2 respectively. Ethylene oxide is produced by catalytic, soft oxidation of ethylene. Comparison of dissolution kinetics of cellulose (mass % of solids residue) in ethylene carbonate, ethylene glycol and polyethylene glycol/EG mixture (80:20) is shown in Fig. 5.

Practically full dissolution of ligno-cellullosic materials in EC requires surplus of the solvent to biomass approx. in mass ratio 4:1 [24], temperature about 150 °C and time between 12 and 17 min.

At longer exposure times the amount of solid residues slightly increases [23,24]. Mixtures of EG with EC with approx. 20–40 mass % of EC are very efficient solvents for biomass [23]. The liquefaction product is a mixture of polyols and phenolic compounds. EC is during the process partly decomposed (in the presence of water) to EG. Cellulose is subjected to partial degradation to levulinic acid in both EG and EC [23].

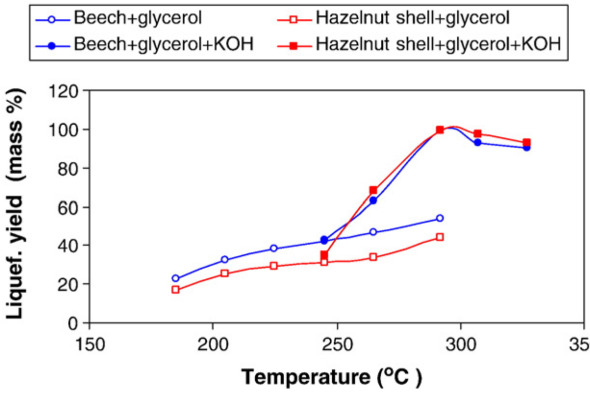


Fig. 4. Comparison of temperature dependencies of liquefaction yields of beech wood and hazelnut shells [44] in pure glycerin (10 g biomass and 50 g glycerol, reaction time 20 min) and in glycerin with KOH (10 g biomass, 230 g glycerol and 5 g KOH, reaction time 20 min).

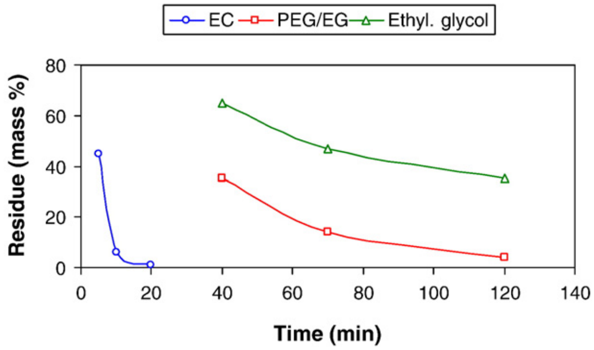


Fig. 5. Residue content after liquefaction of cellulose samples by ethylene carbonate (EC), polyethylene glycol with 20 mass % EG and in ethylene glycol [23]. Temperature 150 °C, cellulose size 70–150 μm, 1 g cellulose, 5 g solvent and 0.15 g 97% H_2SO_4.

The polyols from dissolution of biomass in EG and glycerol are exploited in production of biodegradable polyurethans and epoxy resins.

Physical properties of EG, EC and glycerol are compared in Table 8. Ethylene carbonate is stable in water at temperatures below approx. 120 °C, at temperatures higher than 120 °C degrades rapidly in the presence of alkali hydroxides. All mentioned compounds (EC, EG and glycerol) are biodegradable. Viscosity of esp. glycerol and EG is adjustable by temperature and addition of water or ethanol.

7. Conclusions

As it follows from the analyses of various methods of thermal pretreatment and possible feeding methods of pretreated biomass into pressurized EF gasifier, there is no ideal method and combination. Advantages and disadvantages of individual methods for biomass pretreatment, grinding and feeding are summarized in Table 9.

From the point of view of minimization of overall energy loss, relatively smooth problem-less feeding of biomass (wood, straw etc.) and relatively high heating value of the fuel fed into EF pressurized reactor three methods could be considered:

a) Torrefaction of wood with grinding on particle size below 0.2 mm and utilization of feeding methods developed for dry, pulverized coals. Production of torrefied wood is relatively simple technology. Torrefied wood is suitable for storage and more stable against attacks of microorganisms than dried wood.

b) Preparation of biomass-oil bio-char slurry (content of char between 10 and 25 mass %) and feeding such a slurry by suitable pump with possibility to avoid consumption of an auxiliary gas. In fact for better spraying in the EF reactor some auxiliary gas is often

Table 8
Comparison of EG, ethylene carbonate and glycerol properties.

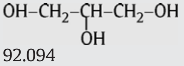
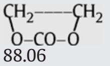
	Ethylene glycol (EG)	Glycerol	Ethylene carbonate
Molecular formula	OH–CH_2–CH_2–OH	 $OH{-}CH_2{-}\underset{OH}{CH}{-}CH_2{-}OH$	 $\underset{O-CO-O}{CH_2{-}CH_2}$
Molar mass (g/mol)	62.068	92.094	88.06
Melting point (°C)	− 12.9	18	35
Boiling point (°C)	197.3	290	250 (partial decomposit.)
Flash point (°C)	111	160	150
Autoignition (°C)	410		465
Density (g/cm^3)	1.113 (25 °C)	1.261 (25 °C)	1.321 (40 °C)
Solubility in water	Soluble (miscible)	Soluble (miscible)	Soluble
Viscosity (mPa s)	16.1 (at 25 °C)	1068 (at 20 °C)	2 (at 40 °C)
HHV (MJ/kg)	19.17	18	13.29

Table 9

Assessment of biomass pretreatments, grinding and feeding methods (in relative loss of heat energy of biomass for grinding 33% efficiency of biomass heat energy transformation to electricity was considered).

Method of pretreatment, grinding etc.	Relat. loss of heat energy for thermal pretr. (%)	Relat. loss of heat energy for grinding (%)	Auxil. gas needs for feeding and pressurizing	Pumping liquid or slurry (LHV)	Problems, disadvantages, price
Drying + grinding $d_p < 0.2$ mm	<6	>18	Need of CO_2 N_2 or superheat. WV	(17–18 MJ/kg)	Smooth feeding is difficult
Drying + grinding $0.5 < d_p < 1$ mm	<6	<9	Need of CO_2 or superheat. Steam	(17–18 MJ/kg)	Smoot feeding is difficult
Torrefaction + grinding $d_p < 0.2$ mm	~10, depending on gas exploit.	<6	Need of CO_2, N_2 or superheat. WV	(20–22 MJ/kg)	Smooth feeding can be attained
Fast pyrolysis (bio-oil only)	~20, depending on char + gas util.	–	–	Pumping bio-oil (16–19 MJ/kg)	Storage problems, corrosion
Fast pyrolysis (bio-oil + char slurry)	10–15, depending on gas util.	<3	–	Pumping Slurry (20–22 MJ/kg)	Storage problems, corrosion
Slurry torrefied wood + glycerol/EG	~10, depending on gas exploit.	<6	–	Pumping slurry (20–22 MJ/kg)	Waste glycerol, EG needed
Slurry dried wood + glycerol/EG	~3 heating of slurry	8–20 dep. on d_p	–	Pumping slurry (18–20 MJ/kg)	Waste glycerol, EG needed
Dissolved wood in EC or EG	~3 heating of solution	8–20 dep. on d_p	–	Pumping liquid	Residues, surplus of EC,EG needed

needed. The fast pyrolysis technology for bio-oil production is more sophisticated than the production of torrefied wood. Long term storage of bio-oil and corrosion properties (due to high content of organic acids) is problematic.

c) Preparation of wood or torrefied wood slurry with waste glycerol or EG and feeding by a pump as slurry. This technology could be elegant under assumption of sufficient amount of waste glycerol or EG.

Total dissolution of lignocellulosic material in a cheap organic solvent (in optimal case either producible from biomass in biorefineries or having the label "waste") would be a desirable method for feeding of biomass generally into pressurized reactors for production of chemicals.

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Symbols and shortenings

d_p:	particle diameter (size)
CFB:	circulating fluidized bed
EF:	entrained flow
EG:	ethylene glycol
EC:	ethylene carbonate
FB:	fluidized bed
HHV:	higher heating value
LHV:	lower heating value
MC:	moisture content of biomass
PEG:	polyethylene glycol
VOC:	volatile organic compounds
WV:	water vapour, steam